Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

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Perspectives Paper

Implications of the coronavirus (COVID-19) outbreak for innovation: Which technologies will improve our lives?

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ABSTRACT

In contrast to earlier coronavirus diseases such as SARS or MERS, whose impact was largely limited to specific regions of the world, the novel coronavirus, COVID-19, is affecting people across the globe. This article analyzes the effects of this worldwide phenomenon on certain technologies and how this may improve our lives. It presents technologies that relate directly to the treatment of the virus as well as those that have been used to adapt to living under this crisis. Given that such a pandemic will likely affect humanity again, this article also highlights how these technologies may prove helpful in the future. To this end, technological challenges, related innovation logics, and their social impacts are discussed.

1. Introduction

The current COVID-19 pandemic is not the first time that a coronavirus outbreak has spread to pandemic levels, as for instance in the cases of SARS and MERS. However, it is the first time that such a pandemic has had a global effect. Recent WHO statistics indicate that almost every country on the planet is now affected by the disease. The worldwide spread of the coronavirus, designated COVID-19, is a disaster in many respects. It has affected not only the personal lives of many across the world, but also entire economies, industries, and nations (UNIDO, 2020). Therefore, this paper investigates if there are any positive effects of the pandemic.

We hence consider the technologies that have evolved as a result of the pandemic, which may result in the development of new and practical solutions to current and future problems, i.e. innovations. In this paper, we identify and discuss ten technologies that are playing a major role in the COVID-19 crisis. These technologies have been selected because some of them have had a fundamental role in responding to the health emergencies of the COVID-19 pandemic. Other technologies have had a essential role in maintaining the business and social functioning of our societies during the lockdown of many economies in the first months of the crisis. Finally, we believe that these technologies are being adopted for the long term and will have a longstanding influence beyond the COVID-19 calamity. Most of the technologies have been in existence since before the COVID-19 outbreak. However, their usefulness and application has been vastly accelerated in light of this crisis.

The remainder of the article is organized as follows. First, we provide an overview of the technologies related to the treatment of coronavirus. Next, we examine the technologies used to adapt to life during the crisis. We conclude with suggestions for future research, focusing on how such technological innovations may be helpful in similar situationsin the future.

2. Life-saving and health-improving technologies during the pandemic

Four technologies are playing an important role in the treatment of coronavirus patients. They are 3D printing, flexible manufacturing systems, big data analytics, and smart healthcare wearables (including smartphones).

2.1. 3D printing

Because the virus spreads through tiny droplets in the air, it is important for health professionals to wear appropriate face masks to protect themselves. However, not every surgical mask is suitable—health professionals require N95 masks with a very close facial fit and very efficient filtration of airborne particles.

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Unfortunately, since the outbreak began, there has been a worldwide shortage of these masks. For example, China, which is responsible for half the total global production of N95 masks, was forced to import masks from other countries such as Japan, India, the United States, and Tanzania (Zhou, 2020). During the crisis, China increased its production capacity (Bradsher and Alderman, 2020). Thereafter, in March, it distributed masks to other countries that desperately required them, such as Italy, the worst-hit European nation, which at one point required 10 million masks, whereas only 10% of that number was available (Zhou, 2020)

In this context, 3D technology has come into use (Jiang et al., 2017). In late March 2020, Copper 3D, a manufacturer of 3D printing materials, published an open-source file for an N95 respirator that could be 3D-printed (Sampol, 2020). Similarly, CoxHealth, an American Hospital non-profit organization, teamed up with Missouri State University's Jordan Valley Innovation center (JVIC) to create 'face shields' for healthcare workers using 3D printing and laser-cutting technology (McConell, 2020).

Ford has also started to produce face shields using its 3D printing capabilities (Etherington, 2020). By sharing these prototypes and 3D printable files, printers all over the world can produce an identical piece of apparatus in minutes. Thus, 3D printing technology has the potential to make on-demand and individual production of these masks possible across the world.

3D printing has also been very useful for the rapid development of valves for respirators. This small piece of equipment is an essential element in respirators, as the valve connects patients under intensive care to breathing machines. For instance, a 3D-printer company in Italy designed a prototype in less than three hours and was then able to make 100 life-saving respirator valves in 24 hours for an Italian hospital that urgently required it (Kleinman, 2020).

2.2. Flexible manufacturing systems

During the current COVID-19 crisis, flexible manufacturing systems have helped some companies to quickly change their production processes and produce some of the tools urgently needed to treat patients in hospitals, for example, ventilators for patients and hand sanitizers for medical staff.

Ventilation is important in the treatment of coronavirus because it is a respiratory disease and may have serious complications for some patients. In the most serious cases, a medical ventilator is necessary to oxygenate the air in the lungs while helping carbon dioxide escape.

Many countries have found themselves lacking the number of ventilators required during the crisis, mostly because they did not have sufficient stock to begin with, or because production had been outsourced to other countries. Even if the existing ventilator manufacturers had ramped up production in the early months of the crisis, there would have been a lack of ventilation and breathing equipment available (Kliff et al., 2020).

To provide for the pressing need for ventilators, some automotive firms, such as Tesla, Ford, and GM, have started to modify their production line to manufacture medical ventilators. However, this is challenging, as "the core technology of today's ventilators is fundamentally different from the manufacturing operations of car manufacturers," according to representatives from the two major ventilator producers, Dräger (Germany) and Medtronic (USA) (Morse, 2020).

Other very important products to fight the spread of coronavirus are hand-sanitizing gels and alcohol wipes. However, stocks of isopropyl alcohol—a vital ingredient for the production of both these products, as well as for everyday use by doctors and nurses in hospitals—are also in short supply across Europe (Pooler and Evens, 2020)

In consideration of this, various spirit manufacturers, from France's Pernod Ricard to small craft-gin distilleries in the UK, are reorienting to increase the production of isopropyl alcohol (Abboud et al., 2020). Meanwhile, LVMH, the luxury conglomerate, is also adapting its production lines to manufacture plastic bottles of hand sanitizers instead of its usual perfume bottles. Sanitizing gel requires three main ingredients: purified water, ethanol, and glycerin, all three of which were already in use by LVMH, and thus, their factory equipment could be quickly adapted to the production of sanitizing gel (Abboud, 2020). Other cosmetic firms have also followed suit, as cosmetics and pharmacy manufacturing are closely related (Arcadi, 2020). This type of frugal, need-based innovation implemented with the resources at hand has spread to new areas during the pandemic (Harris et al., 2020).

2.3. Big data analytics

In July 2020, there were more than 20 public- and private-sector organizations worldwide racing to develop a vaccine against COVID-19 (WHO, 2020). The first was Moderna, an American biotech group, which was able to create a vaccine that was ready for human trials just 42 days after its identification. However, it could take between 12 and 18 months for a vaccine to be available for widespread application to the general public (Kuchler et al., 2020). This is due to the need for larger clinical studies to test the vaccine's efficacy.

An ability to handle clinical and business risks is critical to the development of new medical technologies, including vaccines (Lehoux et al., 2017). Opening up information sources and sharing results is essential for obtaining fast and safe vaccines against COVID-19 (Chesbrough, 2020). One promising technology to accelerate clinical trials is the use of crowdsourced data combined with big data analytics (Wang et al., 2018). Verily, a subsidiary of Google, has been crowdsourcing health data from 10,000 volunteer patients on a daily basis for the past five years, thus creating a kind of kind of "universal control" that eliminates the need for control group testing, which is a lengthy process (CB Insights, 2020). The original project, called Baseline, was developed in May 2019, with the aim of using the data to run more efficient clinical studies in areas such as cancer and mental health, in partnership with pharmaceutical companies. In mid-March 2020, Google opened Verily for Coronavirus tests (Sloane, 2020).

Combined with data analytics, Artificial Intelligence (AI) can also play an important role in the development of healthcare solutions (Hengstler et al., 2016). Google's AI subsidiary, DeepMind, has been using its machine learning technology to identify important proteins that could become drug or vaccine targets for COVID-19 (Fan, 2020). DeepMind has previously worked in partnership with the pharmaceutical company Sanofi to better understand certain crucial diseases, identify the best treatment approach for individual patients, and increase the personalization of healthcare treatment (Terry, 2019).

2.4. Digital healthcare wearables (including smartphones)

Even before the COVID-19 crisis, the global smart wearable healthcare (SWH) market was expected to rise at a rapid pace of more than 5.6% per year, reaching $25 billion USD in 2020 (Papa et al., 2020). The need for detection and monitoring during the crisis has further increased their usage; for example, the Hong Kong authorities require anyone arriving from abroad to wear monitoring bracelets to ensure that they observe a two-week quarantine (Thornhil, 2020). The bracelets carry a QR code that must be paired with a smartphone app. The strength of communications signals such as Wi-Fi or Bluetooth helps determine whether or not the wearer is complying with self-isolation.

Remote healthcare monitoring devices were already in demand before the COVID-19 crisis. A previous study found that the intention to adopt such a device was stronger among respondents who were aware of wearable fitness trackers than among those who were not aware, even before the crisis. (Lee and Lee, 2018).

In addition to dedicated wearable devices, some governments like, those of China, Italy, or Israel, have also used regular smartphones to check whether people stay confined. In China, the monitoring of smartphones, combined with facial recognition cameras is allowing

authorities to identify suspected coronavirus carriers. Meanwhile, mobile applications warn people about their proximity to infected patients in their daily activities (Jaktan, 2020).

These developments in wearables and smartphone applications are also clearly creating new privacy issues (Harari, 2020). However, governments may make the use of such technology mandatory in the future to curb the spread of the virus.

3. Technologies to improve quality of life during the pandemic

One of the main strategies to deal with the spread of COVID-19 has been to confine people to their homes with very limited opportunity to leave, except for essential activities (Cohen and Kupferschmidt, 2020). By March 25th, approximately 2.3 billion people were confined to their homes. Of these, India accounted for 1.3 billion (Suri et al., 2020) with the remaining 900 million in 35 other countries around the world (Agence France-Press, 2020). People confined to their flats and houses have been forced to adopt new behaviors. Such a change has created renewed opportunities in the six following digital technologies.

3.1. Distance education

Distance learning and online learning (sometimes called e-learning) use similar online learning tools, but are actually different in practice and goals. Online learning students can be in the classroom with a professor and only go online to work through their lessons and assessments. With distance learning, students work online at home while the teacher presents lectures and assigns work digitally and remotely (Stauffer, 2020).

In many parts of the world, e-learning was not high on the agenda for schools, universities, and administrations before the pandemic (Stoffregen et al., 2016; Stoffregen and Pawlowski, 2018). However, according to the UNESCO, by March 2020, the COVID-19 crisis had forced more than 1.38 billion students worldwide to stay home (Li and Lalani, 2020). From pre-primary to university education, educational institutions have been obliged to adapt increasingly to distance education and evaluation (Tiejun, 2021). Parents have had to learn how to teach their children with the aid of (and sometimes even without) remote teachers. Therefore, this might lead to more home-based teaching in the future, even when the crisis passes and everyday life returns to normal.

3.2. E-gaming

E-gaming encompasses participation-driven or so-called roleplaying online games where users play a certain role in mobile devices when gaming (Chen et al., 2018). The forced home confinement during the pandemic has generated a boom in the use of online games. The largest video gaming companies have all reported major increases in user numbers (Gough, 2020). For instance, the number of Microsoft Xbox Live users jumped from 65 million during the last quarter of 2019 (Warren, 2019) to 90 million during the first quarter of 2020 (Warren, 2020). Activision, a leading video game publisher, reported that during the first quarter of 2020 the community of Candy Crush players played more game rounds than in any quarter since its acquisition of the game in 2016. The number of active monthly players increased from 249 million in the last quarter of 2019 to 273 million during the first quarter of 2020, an increase of almost 10 percent (Activision, 2020).

Similarly, Chinese-based Tencent, the world's largest video game company, has seen a surge in its revenues for games and video services of more than 30% year-on-year in the first quarter of 2020 alone (Kharpal, 2020).

Additionally, since all national and international sports competitions have been halted worldwide, the most important sporting entities, e.g. FIFA, Nascar, and Formula 1, are turning to e-gaming to soften the financial impact of the postponement and cancelation of sports events while keeping the passion of the fans alive (InsideSport Desk, 2020).

3.3. Videoconferencing

Approximately 200 million Chinese citizens were working remotely as of the end of the Chinese New Year in January 2020 (Bick et al., 2020b). Based on data from the European Union (Eurostat, 2020) and the US government (Desilver, 2019), we estimate that about 110 million people in the EU and 54 million in the US were teleworking as of March 2020. With this rise in teleworking, videoconferencing tools such as Apple's FaceTime, Cisco's Webex, Microsoft's Skype, or Zoom, which have already been in the market for many years (Zec and Matthes, 2018) have experienced huge growth (Lev-Ram, 2020).

In 2017, a study found that 43% of American employees worked remotely with some frequency (Gallup, 2017) and with the COVID-19 crisis, this figure has increased to approximately 90% (Bick et al., 2020a). As people become more familiar with teleworking, the boom in videoconferencing may endure. This could ultimately lead to less face-to-face meetings, less foreign travel for short meetings, and in the long-term, more flexible work environments in a greater variety of industries.

3.4. Internet streaming

The consumption of Internet streaming services has increased significantly due to large-scale confinement. People are consuming more news, movies, and TV shows online (Bhargava et al., 2020) and beyond the general Internet, streaming offers opportunities for real-time information and entertainment (Barnes and Mattson, 2017).

This might lead to the end of traditional broadcast television and mark the rise of Internet streaming (Shim and Shin, 2019), which allows for on-demand streaming of movies and shows.

3.5. Cashless payment

With the omnipresent danger of infection, the use of cash is a risk because the coronavirus may spread through banknotes. Consequently, there has been a surge in cashless mobile payments (Liébana-Cabanillas et al., 2018). In Europe, credit card payments have increased not only because of the rise in e-commerce but also because banks have relaxed the limit for contactless credit card payment in traditional shops (Jones and Nikolaeva, 2020). In countries like China, India, and others, there has been an increase in cashless payments through smartphones (Rooney, 2020). As familiarity with mobile payments increases, its usage could also increase. In Europe and the US, for example, which are far behind China in user adoption of mobile payments, more than 600 million people are already using mobile payments (Fortune, 2019).

3.6. E-commerce and home delivery

In countries where lockdowns are in place, the prohibition or heavy control of retail shopping has resulted in an acceleration in the usage of e-commerce. In the US, the e-commerce penetration rate during the first quarter of 2020 increased from 16% to 27% of total retail; it previously took 10 years to achieve a similar 11% gain, from 2009 to 2019 (McKinsey, 2020). Whereas electronics and apparel have seen a significant rise in popularity among users in the US (Kohan, 2020), the grocery sector has also experienced significant changes. In China, for instance, in the first two months of 2020, online sales of food items increased by 26.4% compared to 20.2% in the same period the year before (Kang, 2020).

The main bottleneck is the lack of delivery employees. While Amazon has been recruiting more than 100,000 people worldwide, many local and regional supermarkets have actually halted or severely limited their online ordering services. Interestingly, the COVID-19 crisis has not pushed the use of drones for home delivery, a technology that Amazon has been developing for years, as its implementation has been delayed mostly for legal reasons (Nakamura and Kajikawa, 2018)

4. Discussion

The recent pandemic has improved our ability to cope with epidemics and other crises through technological and social developments. Before our discussion, we summarize the facts that we introduced in the earlier sections and add a perspective on their long-term implications as the complete disruptive impact of COVID 19 will take months or even years to fully materialize (see Table 1).

In Table 2, we summarize the key lessons learned in the event that such a crisis occurs again.

Our examination of epidemic-related innovation indicates that the time-to-market has been significantly shortened in response to the crisis, as in the case of ventilators.

Innovation processes that would previously have been incremental and taken years have been forced by the global health crisis to move to a more radical model, where big shifts in technology are achieved in days.

Cross-sectoral innovation has seen a significant surge as firms from a wide variety of industries find themselves with excess capacity due to reduced economic activity and decide to use this resource to help overcome the crisis. The convergence of ideas from different entities provides new energy for innovation (Lee and Trimi, 2021). The previously unlikely partnerships of IT firms, auto manufacturers, and hospitals in producing medical equipment is just one example of society uniting to tackle a common adversary. Such restructuring of capacity last occurred during World War II, but what happened in months or years then now happens in hours due to today's communication structures.

The shifts in capacity affect hospitals, manufacturers, providers of communication solutions, small and large firms in general, and society's infrastructure. This will hopefully lead to more flexible structures, with increased preparedness for rapid changes. Multinationals in particular have been pulled out of a profit-maximizing vacuum and forced to realize that those profits depend on the well-being of their employees, society, and the integrity of national infrastructure. The impact of social responsibility driven by the COVID-19 crisis is evidenced by the large number of firms that are willing to contribute to remedying the situation. In such an overwhelming crisis, business leaders realize that they cannot leave the restoration of society to governments alone.

Not only are innovation processes being achieved at an amazing speed, but the adoption of innovation is also surging globally, which has been emerging for several years (Brem and Viardot, 2015). Society is now turning to such processes as a remedy to this critical situation. It will be interesting to analyze if and how those technologies, whose massive adoption has been largely constrained, will continue to be used after the COVID-19 crisis passes. As it is unclear to date how long this crisis will last, and how it may end, these technologies will also evolve further. Another pandemic situation may develop again, which will lead to further unpredictable situations for the whole world. This could have a significant impact on the plans of many countries for the development and deployment of the next generation of digital infrastructure, including 5 G (Shin et al., 2020).

In a pandemic crisis such as COVID-19, individuals are willing to contemplate social innovations they would not have accepted under other circumstances. The control of individual movement and the replacement of humans by artificial intelligence and robots, which were hugely unpopular a few months ago are now increasingly considered attractive solutions. As we overcome this crisis, we must continue to discuss the ethical sustainability of the emergency legal responses and to critically assess the continuity of the established measures.

Organizations are also forced to contemplate solutions they have been previously reluctant to adopt, in order to reduce the spread of the virus. Solutions for telecommuting and flexible work are adapted to different organizational challenges and are given the opportunity to prove their effectiveness. The crisis may forever change how we do business and may mark a huge leap in work–life balance. This is true not only in the context of established companies, but also for entrepreneurs (Giones et al., 2020).

Table 1
COVID-19 crisis short-term and long-term consequences.

Technology	Short-term consequences (1–18 months)	Long-term consequences (beyond 18 months)
1. *3D printing*	-Fast production of medical equipment for hospitals and medical organizations including medical NGOs - New design of healthcare devices to allow for easier 3D printing	- Larger acquisition of 3D printers by hospitals to facilitate local production, if needed. - Increased adoption of 3D technology in automotive, robotics, and manufacturing industries because of faster prototyping and shorter series - Possible development from a B2B into a B2C market with the rise of personal 3D printers by affluent consumers who wish to make their own medical gear at home if needed
2. *Flexible manufacturing systems*	Fast adaptation of production process to manufacture urgently needed medical devices during epidemics (ventilation, hands sanitizers, etc.). - Repatriating of part of pharmaceutical laboratories and production From China and India to Europe and the US	- Redesign of medical devices so they can be manufactured faster and more easily - Redesign of global supply chains for many products and services to make them more resilient (agriculture, energy, etc.) and more geographically diversified
3. *Big data analytics*	- Contribution to the faster development and distribution of new vaccines - Increased use of AI and big data to better understand certain crucial diseases, identify the best treatment approaches for patients, and increase the personalization of healthcare treatment.	- Increased use of data monitoring by companies and governments (automatic tracking of people, goods, etc.) to prevent future epidemics with privacy and political consequences - Increasing demand for cyber-security software and solutions to fight "cyber-crimes" and offer a safer protection of business and personal data
4. *Health care Wearables*	- Accelerated incorporation of more healthcare features into smartphones, smartwatches and other wearable devices - Distance diagnostics, treatment, and monitoring (telehealth) of patients	- Smart health as part of health insurance. - increased adoption of "smart" clothing by consumers - development of virtual fitness and gyms
5. *E-learning*	Short-term option for teaching under quarantine.	- Substitution of in-person classes through digital offerings leading to an increased market share of online programs and curriculums vs. offline programs. - Strong implications on the length, the content, and the pedagogy for these online curriculums
6. *E-gaming*	Significant increase in e-gaming tournaments and participations modelled on offline sport (soccer, tennis, moto, regatta, etc.) instead of only existing games (e.g., Call of Duty, StarCraft2, or Dota2)	- Recognition of virtual games as similar to offline games with professional leagues, top salary star players, merchandising, etc.
7. *Videoconferencing*	Substitute of in-person meetings because of quarantine	- Full home-office working environments. - Reduced travel due to increased use of virtual

(*continued on next page*)

Table 1 (*continued*)

Technology	Short-term consequences (1–18 months)	Long-term consequences (beyond 18 months)
		meetings - Spread of the technology among private users who are usually technology averse (e.g., elderly people)
8. *Internet Streaming*	No opportunities to visit cinemas, etc., leading to dramatic loss of revenues for all sectors of the culture industry, notably live performances such as concerts, operas, etc., as well as the delayed launch of new artists and work (movies, books, albums)	- Tipping point in favor of the consumption of news and entertainment at home, leading to the near disappearance of traditional media (newspapers and movie theatres, for instance) - death of traditional broadcast TV, which will be replaced by streaming – but only if internet bandwidth can cope with increased demand; otherwise, the opposite trend will be seen
9. *Cashless payment*	Fall in the rate of infection through the reduced use of cash	- Online cashless systems retained - Probable domination of mobile payment methods using smartphones over plastic cards.
10. *e-commerce and home delivery*	Increased demand for e-commerce in all affected countries while physical stores are constrained or even shut.	- Strengthened market share of e-commerce in the retail industry. - Accelerated use of robots for packing and drones for delivery to clear the bottlenecks caused by lack of personnel.

Table 2
The impact on society of technological developments during the COVID-19 crisis.

Technological development	Innovation logic	Social impact
Ventilators, vaccines	Time-to-market	Crisis readiness
Artificial intelligence, ventilators	Cross-sectoral innovation	Innovation in ecosystems
Respirators, sanitizers	Flexible manufacturing systems	Social responsibility
Artificial intelligence, robotics	Big data	Intellectual property
Wearables, cashless payment, streaming, e-commerce	Technology acceptance	Citizen surveillance
Videoconferencing, e-learning, e-gaming	Digitization	Flexible work methods

Finally, there is no returning to the "old" normal. Many of the technologies discussed here were already in place before the pandemic but were chiefly used by early adopters, and the COVID-19 crisis has pushed their "forced adoption" (Ram and Jung, 1991; Heidenreich and Talke, 2020) by the majority of users or consumers. The massive testing and diffusion of new technologies have led to leaps in knowledge, which makes them preferable to previous alternatives. For instance, S. Nadella, the current CEO of Microsoft, estimated that with the coronavirus, two years' worth of digital transformation occurred in two months (Sparato, 2020). The improvement of the technologies often makes them preferable to the old alternatives, with solutions developed during the crisis being leaner, more flexible, and more dematerialized than previous solutions (Devezas, 2020).

In other cases, the hurdles of adopting a technology have been overcome. For instance, teleconferencing requires adjusting to displaying and consuming information in a different format. These barriers have now been overcome by many users, and although we will certainly return to physical meetings in some instances, when physical meetings require travel, the cost/benefit ratio will now more frequently tip toward online solutions. Similarly, fast prototyping is an innovation process that is becoming more dispersed and tested. The momentum gained by this and other process innovations makes it more likely that they will develop and prosper.

Even if the pandemic is overcome, other impending crises will require more flexible technologies and a more agile innovation process. As we enter the economic crisis that follows the pandemic and the long-announced climate crisis, we will not only employ the technologies created in response to COVID-19, but also benefit from the innovation processes generated by the current global health crisis.

Contribution statement

Alexander Brem: Conceptualization, Writing - original draft and revisions. Petra Nylund: Writing - original draft and revisions. Eric Viardot: Writing – original draft and revisions.

Supplementary materials

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